522,496

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
5 February 2004 (05.02.2004)

PCT

(10) International Publication Number
WO 2004/012207 A2

(51) International Patent Classification[7]: G21K

(21) International Application Number: PCT/GB2003/003286

(22) International Filing Date: 28 July 2003 (28.07.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/398,599 26 July 2002 (26.07.2002) US

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(81) **Designated States** (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) **Designated States** (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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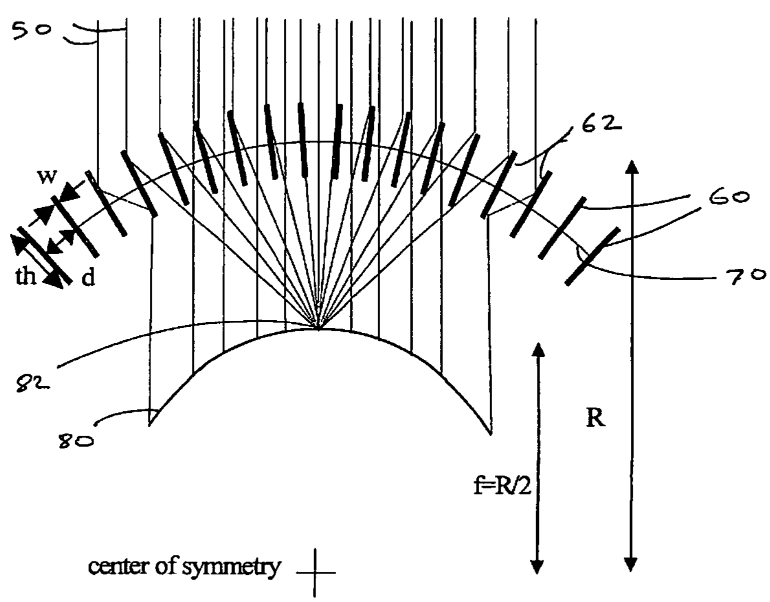
(54) Title: OPTICAL DEVICE



(57) **Abstract:** The invention provides a miniaturized multi-foil object for use in a laboratory environment and other practical applications that require small or portable and/or disposable high energy radiation optics. Specifically, the invention finds utility in high energy lithographic systems, such as X-ray or EUV lithography, as a condenser optic or in topographic systems. In lithographic systems, the present invention exhibits superior symmetry, aperture size, and disposability. Additionally, the multi-foil optic of the invention provides a high throughput efficiency, which is advantageous in many applications.

WO 2004/012207 A2

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

OPTICAL DEVICE

FIELD OF THE INVENTION

The present invention relates to imaging of high energy radiation, such as X-rays. More particularly, the present invention relates to a multi-foil optic device for use in high energy radiation laboratory applications.

BACKGROUND OF THE INVENTION

X-rays and other high energy radiation, such as extreme ultraviolet (EUV) radiation behave differently than electromagnetic radiation commonly encountered, such as that associated with visible light. For example, containment of X-ray radiation and/or focusing of this and other types of high energy radiation is much more difficult than with visible light. Special considerations must be taken into account in applications utilising this and other types of high energy radiation. For example, X-ray imaging systems are particularly difficult to design because of the way in which X-rays interact with matter.

Generally speaking, X-rays that impinge at a normal angle of incidence on any material are largely absorbed rather than reflected. Therefore, normal incidence mirrors used for optical imaging systems, associated with visible wavelengths, are not useful for X-ray imaging systems. Another difficulty is that the index of refraction (n) is approximately one for radiation at X-ray

wavelengths for all materials. Therefore, any refracting imaging system, such as standard optical imaging systems using lenses, which has elements sufficiently thin to transmit X-rays, have extremely long focal lengths, which are not practical for laboratory applications.

However, many materials have an index of refraction that is less than 1 at X-ray wavelengths. For example, the index of refraction at X-ray wavelengths for many materials may be expressed as a complex number as defined by Equation 1 below:

$$n = 1\text{-}d\text{-}ib \tag{1}$$

where d represents absorption of the material and b represents the phase shift of the material, both dependent on the wavelength of the incident X-rays. Thus, as can be seen with reference to Equation 1 above, if d is greater than 0 and b is approximately 0, then the index of refraction (n) is less than 1. Because of this property, it is possible for an X-ray, which is travelling in a medium having an index of refraction of unity (i.e., $n = 1$) such as a vacuum, to undergo "total external reflection," for certain angles of incidence. Total external reflection is analogous to "total internal reflection" commonly associated with visible wavelengths of light and governed by Snell's law.

For X-rays to undergo total external reflection, when travelling from a vacuum having an index of refraction of 1, to a material for which the index of refraction is less than 1, as defined by Equation 1 above, certain conditions must be met. These conditions are defined by Snell's law, which states that X-rays will undergo total external reflections for angles θ, where:

$$\theta < \theta_c \tag{2}$$

and where:

$$\cos \theta_c = 1\text{-}d \tag{3}$$

where d is the material parameter associated with the index of refraction at X-ray wavelengths of the material upon which the X-ray is incident, and θ_c is the critical angle for total external reflection. The critical angle may also be approximated by Equation 4 below:

$$\theta_c \approx \sqrt{2d}$$

The parameter d of the index of refraction (n) is proportional to the atomic number (Z). Thus, the critical angle θ_c is also essentially proportional to the atomic number of the material upon which the X-rays are incident. Therefore, materials having high atomic numbers reflect X-rays more efficiently than materials having low atomic numbers (i.e., the critical angle θ_c is larger for materials with a higher atomic number Z). For example, gold and nickel are commonly used as reflecting materials for X-rays. The critical angle θ_c for X-rays incident upon these elements, where the X-rays have an energy of approximately 1 keV, is about 1°. Therefore, according to Equations 2 and 3 above (and based on Snell's law), X-rays having an energy 1 keV would experience total external reflection as long as they were incident at an angle less than about 1°. Therefore, from the above, it can be seen that any system used to reflect X-rays would necessarily make use of small angles of incidence between the X-rays and the reflecting material.

Many advances in X-ray optics have come in the field of astronomy. Astronomers have used various techniques to image X-ray radiation from astronomical sources using large telescopes. For example, one method of focusing X-rays in astronomical telescopes has been proposed, which utilises a set of non-parallel flat metal foils set at correct angles to focus incident X-ray radiation for proper imaging. One particular type of this X-ray imaging is known as "lobster-eye" optics, named after the construction of a lobster's eye, as found in nature. An in-depth discussion of lobster-eye optics can be found in Instrumentation for a Next-Generation X-Ray All-Sky Monitor; A.G.

Peele, Code 662, available from the Laboratory for High Energy Astrophysics at the Goddard Space Flight Center in Greenbelt, Maryland.

X-ray optics used in astronomical devices, such as telescopes, are typically large assemblies, usually on the order of about 0.027 m^3. Such large optic devices serve to collect the maximum possible radiation from weak, distant sources. While such large devices are ideal for use in space with astronomical applications, as they can be easily manoeuvred there, they are cumbersome and difficult to use in any type of earth-bound laboratory applications. Also, X-rays reaching the Earth from space are virtually normal to the Earth's surface and so there is less of a requirement to control divergence or minimise the spacing between foils. However, the abilities of such astronomical devices could be useful in laboratory applications.

Therefore, it would be desirable to create a miniaturised version of such collector optics for X-rays and other high energy radiation for use in laboratory applications. These laboratory-sized, miniature collector optics should exhibit similar performance advantages to their larger astronomical cousins, but without the cumbersome size generally associated with larger optics.

Other optical devices could benefit from a decrease in overall size and, specifically, the spacing between elements. For example, in collimating devices, such as Soller slits, it is desirable to decrease the thickness of the collimating blades and to reduce the spacing between the blades.

SUMMARY OF THE INVENTION

Accordingly, the present invention achieves the foregoing objectives by way of an optical device configured for use in laboratory applications. The optical device of the present invention overcomes difficulties associated with creating such optics on a miniature scale. Specifically, by way of the precisely spaced and tightly controlled positions of elements of the optical device of the present invention, applications requiring focusing of X-rays or other high energy radiation in a laboratory environment may be supported.

In accordance with an embodiment, the present invention provides an efficient collector optic that can be used as a first optic in a system for X-ray or EUV lithography. This embodiment of the present invention is a multi-foil optic, which advantageously provides a large optical aperture and high efficiencies, both of which are desirable in laboratory applications such as lithography. Additionally, the multi-foil optic exhibits a square, symmetry, which is advantageous for lithography and other applications.

The foregoing features of the invention, and the advantages achieved thereby, are explained in greater detail hereinafter with reference to particular embodiments illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram of a lobster-eye multi-foil optic in accordance with an embodiment of the present invention.

Fig. 2 is a block diagram of a lithographic system in which the present invention may be utilised.

Fig. 3 is a schematic diagram of a Soller slit in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

To facilitate an understanding of the principles that underlie the present invention, it will be described hereinafter with particular reference to its implementation in connection with X-ray lithography. It will be appreciated, however, that the practical applications of the invention are not limited to this particular embodiment. Rather, the invention will find utility in a variety of different applications in which efficient X-ray or other high-energy optics for use in laboratory environments are required.

Figure 1 illustrates a basic lobster-eye optic system for focusing X-ray radiation 50. The lobster-eye array of mirrored plates 60 provide a number of flat surfaces 62 which are normal to an outer arc 70 of a first circle, and focus X-ray radiation 50 to a point 82 on a detector surface 80. This is shown as an arc of a second circle, which is concentric with the first circle. Only one dimension of the lobster-eye optic is shown in Figure 1. However, those skilled in the art will recognise that the lobster-eye optic may preferably be adapted as a two-dimensional optic device. In such a case, a second set of mirrored surfaces 62 are provided which are substantially normal to the first set.

This type of X-ray optic is based on the total external reflection of X-rays incident at angles smaller than the critical angle θ_c from flat surfaces. An example of a lobster-eye optic, which forms a part of an X-ray topography system can be seen in commonly assigned U.S. Patent Application No. 10/004,785 to Bowen et al., filed on December 7, 2001, which is entitled, "X-Ray Topographic System."

While such lobster-eye optics have been proposed for use in astronomical telescopes, these optics are typically large assemblies of about 0.027 m^3. Such large optics are easily used and maneuvered in a cosmic environment, but are difficult to use with any laboratory applications or in a terrestrial laboratory environment.

According to an embodiment of the present invention, however, a miniature version of such a lobster-eye optic, having a size of about 125 mm^3 is provided. In accordance with the present invention, all measurements, spacings, and manufacturing qualities must be closely monitored and maintained within a small margin of error, if a multi-foil optic on such a small scale is to work properly. Obviously, as can be seen from the relatively small critical angle θ_c, placement precision of the optical reflecting elements is critical, and must be controlled to within much less than 1°. For example, in accordance with an embodiment of the present invention, placement of the reflective elements or plates 60 must be controlled to within about 0.01° for lithographic applications. For crystal optic applications, in accordance with embodiments of the present invention, placement of the reflective elements 60 must be controlled to within about 0.002°.

To achieve such precise positioning of the optical reflecting elements 60, a micro-positioning device, such as a modified goniometer, may be used. While conventionally used to measure crystal angles, the device may be modified to measure the position of the foils.

In addition to precision placement of the optical elements 60, all of the flat reflecting surfaces 62 should be coated to increase their reflectivity. Typical coating materials include gold, platinum and glass. Each of these surfaces 62 must have a highly reflective coating to properly reflect the X-ray radiation 50. The coating could be one of metal or glass or another highly polished reflection coating. Roughness of the foils that form the reflecting surfaces, in accordance with an embodiment of the present invention, should preferably be 3 Angstroms or less. Waviness of the foils must also be low, with a slope error of less than 0.05° for lithographic applications and less than 0.002° for crystal optics.

It has been found that thin foils can be produced from materials having a low density, such as glass or mica. Conventionally, it has been thought that high density materials were required to avoid absorption of the X-rays. However, foils made from low density materials, having a density of less than 6 g/cm^3, can be made thinner and longer without experiencing distortion of the foils. The thickness (w) of the foils can be in the range of 5 to 300 microns. A decrease in the spacing (d) between foils means that the angle of incidence will be less than the critical angle.

The spacing (d) between foils can be reduced by precisely positioning each of the foils and then fixing the spacing (d) using fixing means. This fixing means can include bonding of the foils using an appropriate adhesive, such as an epoxy. The bonding material should allow the transmission of X-rays through the material.

Advantageously, a multi-foil optic, according to embodiments of the present invention, has multiple uses in laboratory applications, which to this point have yet to be explored because no multi-foil optic of a convenient size for laboratory applications has been developed. However, the multi-foil optic provides an efficient collector optic that may be used as the first optic in a system for high energy radiation lithography, such as EUV or X-ray lithography. This is partly because the multi-foil optic provides a large aperture and high throughput efficiencies. Additionally, such a miniature multi-foil optic is advantageous as it does not require uniformity of the reflecting surface over such a large length, as would be necessary, for example, in an astronomical telescope or other device having large reflecting surfaces.

Figure 2 illustrates a block diagram of a basic high energy radiation lithographic system 20 in which the multi-foil optic may be used. In Figure 2, a source 22 provides a beam of energy that is focused by way of a condenser optic 24 onto a lithographic mask 26. The mask 26 is a pattern that is

desirable to be imprinted on a specimen, such as a semiconductor wafer, for example. Energy transmitted through the mask 26 is focused by way of a second set of optics 28 onto the specimen 30 to create the desired pattern thereon. High energy radiation or X-ray lithography is desirable in general as it decreases the feature size that can be imprinted on a particular specimen 30. Therefore, on a semiconductor wafer for example, many more transistors could be imprinted using X-ray lithography than would be possible with traditional lithographic systems, which helps produce more efficient electronic devices.

In Figure 2, the condenser optic 24 could be replaced by a hybrid optic comprising the multi-foil optic and another optic for further tailoring the beam (e.g., a polycapillary optic, etc.). By utilising the multi-foil optic in a lithographic system, such as the system shown in Figure 2, several advantages are achieved. First, the aperture of the multi-foil optic is larger than apertures traditionally used in such systems. For example, traditional systems are able to achieve aperture sizes of approximately 20mm X 20mm, while the present invention is able to provide aperture sizes of about 50mm X 50mm.

Additionally, the multi-foil optic exhibits a naturally square symmetry. A square symmetry is advantageous in lithography, as both masks and specimens often have square geometries, and the multi-foil optic is better adapted to imaging in such a system. Moreover, the angular range of the multi-foil optic of the present invention can be easily extended by using multi-layer coatings on each plate.

Another advantage of utilising the present invention in a high energy lithographic system, such as the system shown in Figure 2, is that it avoids problems associated with contaminated condenser optics. Condenser optics are usually expensive, and therefore, the present invention has the advantage of being disposable. For example, in X-ray lithography, X-ray sources, such as the source 22 shown in Figure 2, are generally dirty sources that

contaminate the condenser optics 24. For example, a source may comprise lasers hitting and vaporising a metal foil, such as a copper foil, to create a plasma of multiply charged ions. It is these ions that generate the X-rays used in the system. This process of vaporisation creates sputtering that contaminates the condenser optic 24 of a high energy lithographic system. Because the multi-foil optic of the present invention is less expensive however, it can be disposed of when it becomes contaminated and replaced by another multi-foil optic.

A further advantage of the multi-foil optic is a high throughput efficiency for the high energy radiation being used. For example, in a high energy lithographic system, such as the one shown in Figure 2, for example, the multi-foil optic of the present invention provides higher throughput efficiencies than most traditional condenser optics 24 used in such systems. Conventional ellipsoids of revolution, for example, give an annular beam with a hole in the centre, which is very inconvenient for many applications. Polycapillary optics avoid the beam problems associated with the ellipsoids of revolution, but lose efficiency at larger sizes, and has a maximum semi-angle of only 6°. The multi-foil optic provides a throughput efficiency much greater than those associated with both ellipsoids of revolution and polycapillary optics, and should be able to at least double the maximum semi-angle (i.e., the angular aperture) associated with polycapillary devices, while achieving at least three times the transmission efficiency of such a device.

From the foregoing, it can be seen that the present invention provides an optical device that is convenient for use in laboratory applications requiring focusing of high energy radiation, such as X-rays. One such laboratory application in which the present invention can be utilised is that of high energy or X-ray lithography. In such an application, the present invention exhibits superior symmetry, efficiency, and aperture size, and is disposable, preventing need for re-using expensive, contaminated condenser optics.

It will be appreciated by those of ordinary skill in the art that the present invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. For instance, while an exemplary embodiment of the invention has been described with reference to X-ray and other high energy lithography, the principles of the invention are applicable to all applications in which it is desirable to have a miniaturised, disposable multi-foil object for focusing X-rays or other high energy radiation. Also, the present invention is applicable to collimating devices, such as Soller slits. A Soller slit according to the present invention is shown in Figure 3. In this figure it can be seen that the Soller slit allows radiation 50 which is substantially parallel to the plates 60 to reach the detector 80. However, the surfaces 62 of the plates 60 are non-reflective and divergent radiation 50 does not pass the Soller slit. Therefore, the radiation 50 is collimated.

The presently disclosed embodiments are, therefore, considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

CLAIMS:

1. An optical device comprising:

a plurality of plates providing a plurality of flat surfaces positioned to provide either total external reflection or collimation of high energy radiation from a high energy radiation source, the plurality of plates located either after the radiation source or before a detector positioned to receive high energy radiation reflected from or collimated by the plurality of flat surfaces; wherein

the plurality of flat surfaces are non-parallel.

2. The optical device of claim 1, wherein either the source or the detector define an arcuate surface and each of the plurality of flat surfaces is substantially normal to the arcuate surface.

3. The optical device of claim 1 or 2, wherein the high energy radiation comprises X-ray radiation.

4. The optical device of claim 1 or 2, wherein the high energy radiation comprises extreme ultraviolet (EUV) radiation.

5. The optical device of any preceding claim, further comprising fixing means for fixing the position of the plurality of plates relative to each other.

6. The optical device of claim 5, wherein the fixing means is transmissive to the high energy radiation.

7. The optical device of any preceding claim, wherein the plurality of plates includes a coating material.

8. The optical device of any preceding claim, wherein the plurality of plates are formed from a material having a density less than 6 g/cm^3.

9. The optical device of any preceding claim, wherein the fixing means comprises an adhesive.

10. The optical device of any preceding claim, further comprising a positioning device for the positioning the plurality of plates relative to each other.

11. The optical device of any preceding claim, wherein the optical device is a multi-foil optic.

12. The optical device of any preceding claim, wherein the optical device is a Soller slit.

13. A method for performing high energy radiation lithography, comprising the steps of:

receiving high energy radiation from a high energy radiation source;

focusing the high energy radiation from the high energy radiation source using an optical device;

receiving the focused high energy radiation from the optical device onto a lithographic specimen via a lithographic mask.

14. The method of claim 13, wherein the high energy radiation comprises X-ray radiation.

15. The method of claim 13, wherein the high energy radiation comprises extreme ultraviolet (EUV) radiation.

16. A high energy lithographic system, comprising:

a high energy source;

an optical device for focusing high energy radiation from the high energy source;

a mask, which receives focused high energy radiation from the optical device; and

a specimen, which is imprinted with the pattern of the mask by the high energy radiation passing therethrough.

17. The high energy lithographic system of claim 16, wherein the high energy radiation comprises X-ray radiation.

18. The high energy lithographic system of claim 16, wherein the high energy radiation comprises extreme ultraviolet (EUV) radiation.

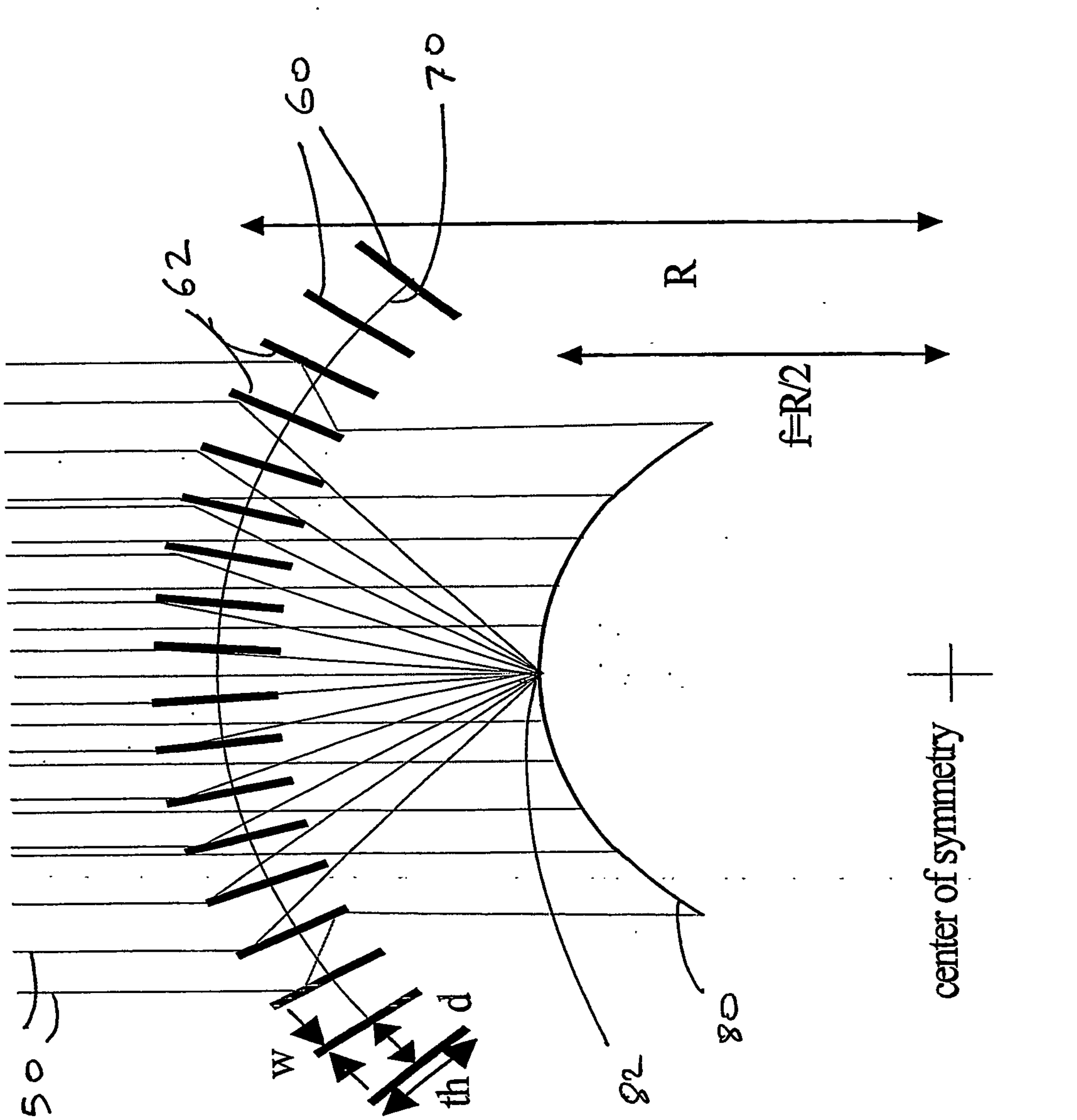


Fig. 1

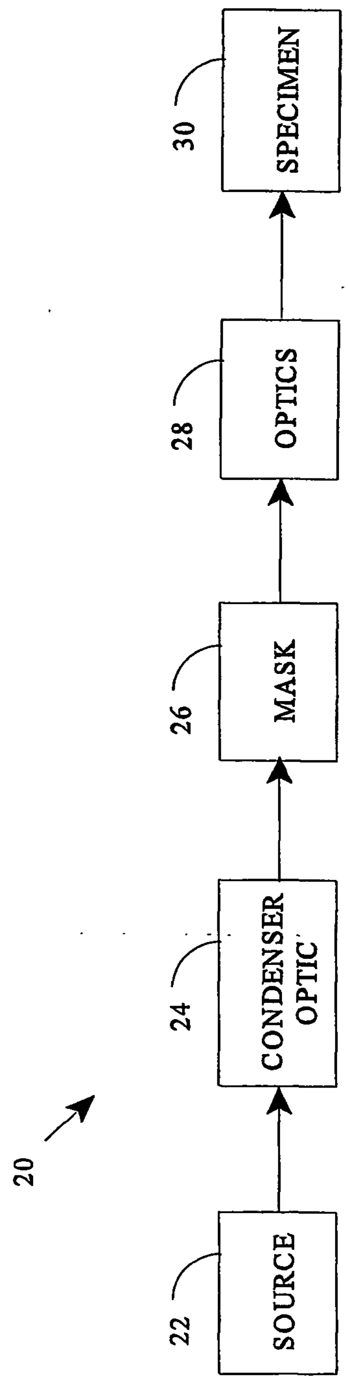

30
SPECIMEN
28
OPTICS
26
MASK
24
CONDENSER OPTIC
20
22
SOURCE

Fig. 2

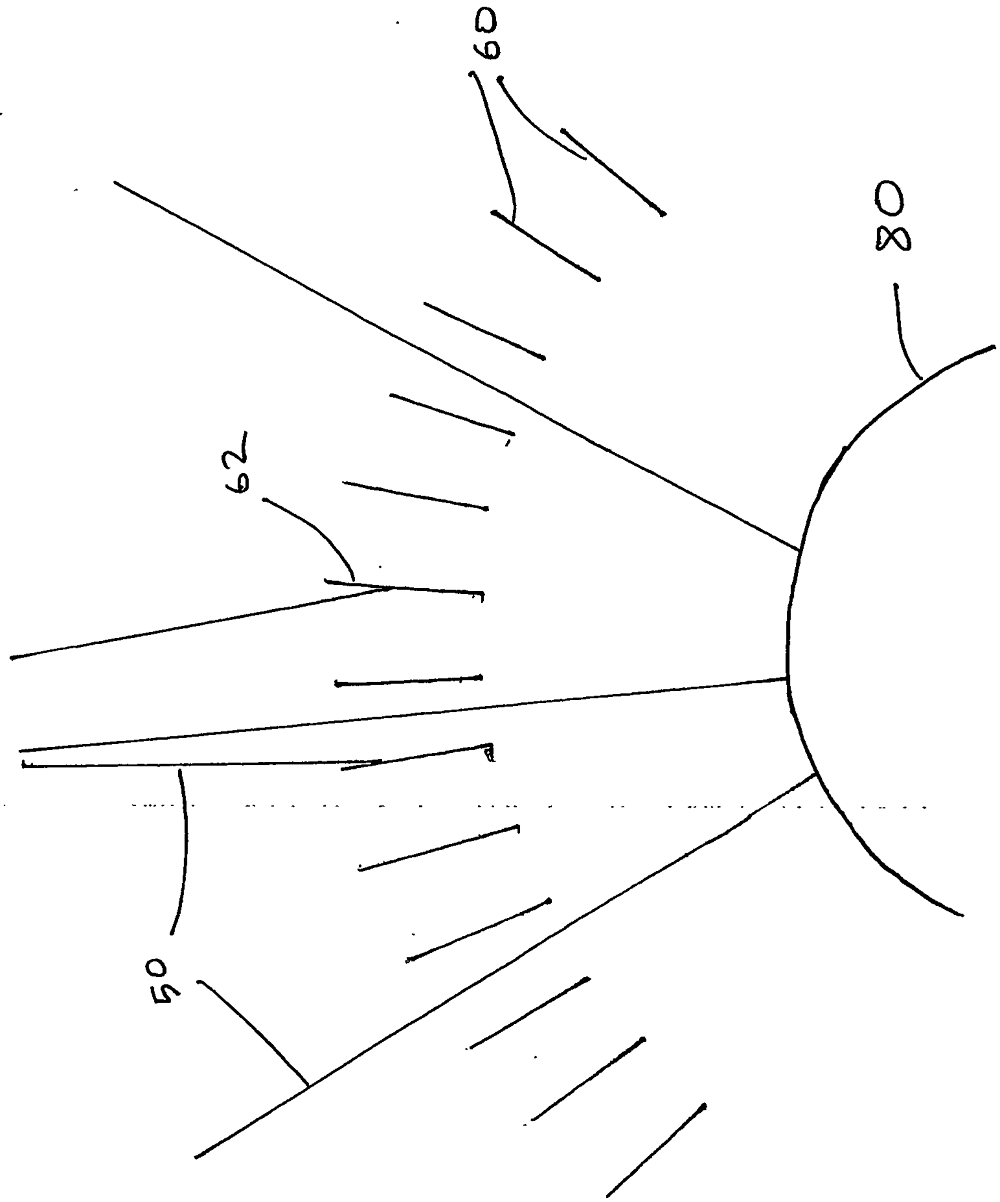


Fig 3